AXIOMATIC DESIGN APPLIED TO INJECTION MOULDS FOR PLASTICS PARTS

Abstract

Traditionally, the design process is one of the few technical areas where experience is generally more important than formal education. Usually it follows a recursive and repetitious process, characterized by trial and error. This paradigm of product development is expensive, unpredictable and prone to failures. To achieve success, companies must design the product right at the first time, since even an inordinate amount of investment in the subsequent manufacturing processes cannot overcome errors committed during the design stage of product development.

Based upon this reality, companies may approach product development in a systematic and scientific basis, which can provide designers with the benefit of scientific tools that can assure them complete success. Design axioms [1], as a special set of principles, provide a systematic search process through the design space to minimize the random search process and determine the best design solution amongst many alternatives.

In the literature, previous work demonstrated the numerous benefits obtained by the Axiomatic Design (AD) approach in some industrial and organizational areas. Our paper will explain how this method can be applied to the mould design process, and suggests a few changes that should be made to the conventional process adopted, according to the AD principles.

Introduction

Currently, markets impose rapid and constant changes in the business environment. To seek competitiveness companies must therefore have high adaptation/innovation speeds to adapt to such changes and assume as a key for their success efficient product development.

The Axiomatic Design (AD) approach, proposed by N.P.Suh [1], is a scientific way of viewing design that provides an underlying framework for understanding design activities. The ultimate goal of AD is to establish a scientific basis for design. This method provides the designer with a theoretical foundation based on logical and rational thought processes and tools, with the final goal of improving design activities. In accomplishing this goal, AD provides a systematic search process through the design space to determine the best design solution amongst many alternatives.

Axiomatic Design

The basic postulate of the axiomatic approach to design is that there are fundamental axioms that govern the design process. Two axioms were established by examining the common elements that are always present in good designs, be it a product, process, or a systems design. They were also identified by examining actions taken during the design stage that resulted in dramatic improvements [2]. The first axiom is called the Independence Axiom. It states that the independence of Functional Requirements (FRs) must always be maintained, where FRs are defined as the minimum number of independent functional requirements that characterize the design goals. The second axiom is called the Information Axiom, and it states that amongst several designs that satisfy the Independence Axiom (good design), the design that has the smallest information content is the best design.

Axiom 1 (The Independence Axiom): Maintain the independence of the Functional Requirements (FRs)

Axiom 2 (The Information Axiom): Minimize the information content of the design.

Besides these two axioms, eight corollaries and twenty seven general theorems have been developed to guide and evaluate specific types of design [1].

The design process progresses from abstract concepts to detailed information in a top-down hierarchical manner. This process starts with the identification of the customer’s attributes (established in the Customer domain), which are then translated to specific requirements, the FRs formalized in the functional domain. Afterwards, a physical embodiment characterized in terms of Design Parameters (DPs) must be created with the objective to satisfy the FRs and Constraints (Cs). According to Suh [1], these mapping between FRs and their respective DPs constitute the design process.

Finally, and adopting a similar procedure, the product specified in terms of DPs should be related with Process Variables (PV), that assure its production.

The design process may be represented in terms of a design hierarchy, and such hierarchies do exist for both the functional and the physical domains. The decisions made at higher levels affect the statement of the problem at lower levels, since the hierarchical decomposition in one
domain cannot be performed independently of the evolving hierarchies at other domains.

First, a top level set of FRs must be developed for the system and define the entire scope of requirements for the system, so that they don’t overlap the requirements which they define. Once the top level FRs are defined, they are mapped, or zagged, to DPs at the same level of detail. Then, the top level FRs and DPs are both decomposed, or zagged, through a series of levels of detail, such as system, sub-system, component, and function. This process continues until one achieves a level where the design may be described parametrically (see Figure 1).

At each level of decomposition, a design matrix $[A]$ is developed, which relates the FRs to their associated DPs, at each level. When working at the top-level design matrices, they can initially be populated with an X or 0, respectively, indicating a mapping relationship (X) or lack of mapping relationship (0). Mathematically, the relationships between the FRs and DPs are expressed as:

$$\{FR\} = [A]\{DP\}$$

(0.1)

Where $\{FR\}$ is the functional requirement vector, $\{DP\}$ is the design parameter vector, and $[A]$ is the design matrix that characterizes the design. The structure of $[A]$ defines the type of design being considered, and can assumed under the following three different forms [3]: Firstly, and the most preferred one, we have the Uncoupled Design. In this design, the $[A]$ matrix is a diagonal matrix, indicating the independence of FR-DP pairs. Therefore, each FR can be satisfied by simply considering the corresponding DP. Secondly, the Decoupled Design encompasses designs where the design matrices are triangular. Finally, we have the Coupled Design (undesirable), where the design matrix has no special structure (the design matrix consists of mostly non zero elements). Thus, a change in any DP may influence all FRs simultaneously.

An uncoupled design satisfies Axiom 1, whereas in a coupled design some of the functions depend upon other functions, thus violating Axiom 1. In a decoupled design the DPs can be independently determined through an ordered adjustment which guarantees the independence of FRs. This design is inferior to an uncoupled design in the sense that it may require additional information content.

During the mapping process there can be many design solutions for one problem description, due to high probability of identifying different ways of fulfilling each of the FRs by several DPs. Hence, to deal with this problem the design axioms are used to determine the acceptable designs by provide the criteria to evaluate them. In this context, during the mapping process where one goes from the functional domain to the physical domain, the designer must take the correct design decisions using the Independence Axiom. This axiom states that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FR. This means that the designer must choose a correct set of DPs to be able to satisfy the FRs and maintain their independence. Afterwards, when several designs that satisfy the Independence Axiom are available, the Information Axiom should be used to select the best design, i.e., the one that has the smallest information content.

**Axiomatic Design applied to mould design**

Moulds for the production of plastic parts must be custom designed and built. Usually, no formal structural analysis is performed on the mould design. The designer traditionally relies on his skills and intuition, and follows a set of general guidelines for designing plastic injection moulds. This process doesn’t ensure that the mould design is acceptable and is the best option. Therefore, it’s important to understand the logic behind the guidelines and to identify the moulds’ functions. The AD approach can be adopted to achieve such a goal.

To conduct the AD, one must identify the FR’s and the DP’s by a zigzag process, for several levels. To undergo this exercise, one will admit a typical process of mould design which is applied by a majority of mould makers, as identified by a multidisciplinary team (who have received knowledge about AD concepts). Therefore, to develop the mapping between FR-DP, it is necessary, firstly, to define the FR at the highest level of hierarchy in the functional domain. At this stage many FR may be established, so extreme care needs to be taken to assure all FR are taken into account before a single FR is adopted. In this work the highest FR established was: FR – Injection of the plastic part. The DP which satisfies this FR was: DP – Cavity’s number of the mould. Afterwards, for the second level, the FR previously
identified was decomposed in lower FRs (based on a zag process), such as:

- **FR1** – Assure the structural resistance of the mould;
- **FR2** – Allow the flux of the melt from the injection nozzle into the mould;
- **FR3** – Control of the mould’s temperature;
- **FR4** – Allow the release of the part to the mould;
- **FR5** – Assure dimensional reproducibility;
- **FR6** – Allow for the relief of gases/air;
- **FR7** – Define the volume and the form of the plastic parts;
- **FR8** – Allow for the transportation of the mould.

Then, with the purpose of identifying the respective DPs at the 2nd level, which assure the previous eight FRs, one moves again from the functional domain to the physical domain (zig process). The DPs defined are:

- **DP1** – Mould’s structure;
- **DP2** – Injection system;
- **DP3** – Temperature system;
- **DP4** – Type of Ejection system;
- **DP5** – Mould material selection;
- **DP6** – Air gap system;
- **DP7** – Part’s geometry and shrinkage;
- **DP8** – Transportation system.

Once the FR and DP are defined at this level, one may develop the corresponding design matrix, which provides the relationships between the FR and DP elements:

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3 \\
FR_4 \\
FR_5 \\
FR_6 \\
FR_7 \\
FR_8
\end{bmatrix}
= \begin{bmatrix}
X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & X & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & X & 0 & X & 0 & X & 0 \\
0 & 0 & 0 & X & 0 & 0 & X & 0 \\
0 & 0 & X & X & X & X & X & 0 \\
0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3 \\
DP_4 \\
DP_5 \\
DP_6 \\
DP_7 \\
DP_8
\end{bmatrix}
\]

(0.2)

This design matrix was analysed, with the aim of evaluating if it satisfies the Independence axiom. Based on the previous design matrix, it is possible to verify that this design matrix is coupled. This fact doesn’t cause too much concern because in this work our goal was to identify how the mould design is currently developed and understand the connected problems related with it.

The next steps in this application were to decompose the eight FR already identified into the subsequent levels, and determine the corresponding DPs.

- **FR11** – Coupling the mould to the injection machine;
- **FR12** – Alignment of the two half parts of the mould;

The corresponding DPs are:

- **DP11** – Fixing plate’s dimension
- **DP12** – Locating and guidance system

\[
\begin{bmatrix}
FR_{11} \\
FR_{12}
\end{bmatrix}
= \begin{bmatrix}
X & 0 \\
0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{11} \\
DP_{12}
\end{bmatrix}
\]

(0.3)

At the 3rd level:

- **FR121** – Guarantee the adjustment of the 2 halves of the mould
- **FR122** – To line up the cavity and the core of the mould
- **FR123** – To centre the injection nozzle

And DPs:

- **DP121** – Dimensions of the Interlocking System
- **DP122** – Guidance system dimension or selection
- **DP123** – Locating ring selection

\[
\begin{bmatrix}
FR_{121} \\
FR_{122} \\
FR_{123}
\end{bmatrix}
= \begin{bmatrix}
X & X & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{121} \\
DP_{122} \\
DP_{123}
\end{bmatrix}
\]

(0.4)

For the **FR2**, the subsequent levels are:

- **FR21** – Allow the access of the melt into the mould
- **FR22** – Melt distribution
- **FR23** – Admission of the melt into the impression zones

\[
\begin{bmatrix}
FR_{21} \\
FR_{22} \\
FR_{23}
\end{bmatrix}
= \begin{bmatrix}
X & X & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{21} \\
DP_{22} \\
DP_{23}
\end{bmatrix}
\]

(0.5)

At the 3rd level:

- **FR221** – Fast filling of the impression
- **FR222** – Balance the melt flux
- **FR223** – Section dimension
- **FR224** – Length dimension

\[
\begin{bmatrix}
FR_{221} \\
FR_{222} \\
FR_{223}
\end{bmatrix}
= \begin{bmatrix}
X & X \\
0 & X \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{221} \\
DP_{222} \\
DP_{223}
\end{bmatrix}
\]

(0.6)

For the **FR3**, the subsequent levels and the corresponding DPs are:

- **FR31** – Slow down the solidification
- **FR32** – Allow part solidification
- **FR33** – Mould material selection
- **FR34** – Type of Ejection system
- **FR35** – Mould material selection
- **FR36** – Air gap system
- **FR37** – Part’s geometry and shrinkage
- **FR38** – Transportation system

\[
\begin{bmatrix}
FR_{31} \\
FR_{32} \\
FR_{33}
\end{bmatrix}
= \begin{bmatrix}
X & X & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_{31} \\
DP_{32} \\
DP_{33}
\end{bmatrix}
\]

(0.7)

At the 3rd level:
FR_{321} – Efficient removal of heat
FR_{322} – Uniform removal of heat
DP_{321} – Dimension of the water (fluid) circuit

\[
\begin{align*}
\{ FR_{321} \} &= \begin{bmatrix} X & X \end{bmatrix} \{ DP_{321} \} \\
\{ FR_{322} \} &= \begin{bmatrix} X & X \end{bmatrix} \{ DP_{322} \} \\
\end{align*}
\]

(0.8)

For FR_{4}, the subsequent levels are:

FR_{41} – Allow the displacement of ejection plates
FR_{42} – Assure the ejection of the part’s negative zones
FR_{43} – Assure the global ejection
FR_{44} – Allow the return of the ejection system

The corresponding DPs are:

DP_{41} – Fixing Hole for the injection machine’s hydraulic cylinder
DP_{42} – Jiggle Pin’s Geometry
DP_{43} – N.º ejectors pins
DP_{44} – Return Pins

\[
\begin{align*}
\{ FR_{41} \} &= \begin{bmatrix} X & 0 & 0 & 0 \end{bmatrix} \{ DP_{41} \} \\
\{ FR_{42} \} &= \begin{bmatrix} 0 & X & 0 & 0 \end{bmatrix} \{ DP_{42} \} \\
\{ FR_{43} \} &= \begin{bmatrix} 0 & X & X & X \end{bmatrix} \{ DP_{43} \} \\
\{ FR_{44} \} &= \begin{bmatrix} 0 & 0 & 0 & X \end{bmatrix} \{ DP_{44} \} \\
\end{align*}
\]

(0.9)

At the 3rd level, for FR_{43}:

FR_{431} – Minimize marks on the plastic part
FR_{432} – Guarantee the part’s releasing
DP_{431} – Ejection pin diameter
DP_{432} – Ejection pin length

\[
\begin{align*}
\{ FR_{431} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{431} \} \\
\{ FR_{432} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{432} \} \\
\end{align*}
\]

(0.10)

At the 3rd level, for FR_{44}:

FR_{441} – Protect ejection components when the mould closes-up
FR_{442} – Guarantee stability
DP_{441} – Return Pin’s length
DP_{442} – Return Pin’s diameter

\[
\begin{align*}
\{ FR_{441} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{441} \} \\
\{ FR_{442} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{442} \} \\
\end{align*}
\]

(0.11)

For FR_{6}, the subsequent levels are:

FR_{61} – Gas liberating sectors due to gas accumulation
FR_{62} – Reduction of the pressure made by the gases
DP_{61} – Define depth
DP_{62} – Venting localization

\[
\begin{align*}
\{ FR_{61} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{61} \} \\
\{ FR_{62} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{62} \} \\
\end{align*}
\]

(0.12)

For FR_{7}, the subsequent levels are:

FR_{71} – Guarantee the finishing
FR_{72} – Define the internal impression of the part
FR_{73} – Define the external impression of the part
FR_{74} – Reproduction of the part’s details
FR_{75} – Guarantee detailed part definition

And the corresponding DPs are:

DP_{71} – Product’s surface finish type
DP_{72} – Core’s geometry
DP_{73} – Cavity geometry
DP_{74} – Inserts geometry

\[
\begin{align*}
\{ FR_{71} \} &= \begin{bmatrix} X & 0 & 0 & 0 & 0 \end{bmatrix} \{ DP_{71} \} \\
\{ FR_{72} \} &= \begin{bmatrix} X & X & 0 & X \end{bmatrix} \{ DP_{72} \} \\
\{ FR_{73} \} &= \begin{bmatrix} X & 0 & X & X \end{bmatrix} \{ DP_{73} \} \\
\{ FR_{74} \} &= \begin{bmatrix} X & X & X & X \end{bmatrix} \{ DP_{74} \} \\
\{ FR_{75} \} &= \begin{bmatrix} X & X & X & X \end{bmatrix} \{ DP_{75} \} \\
\end{align*}
\]

(0.13)

Finally, for the last FR, FR_{8}, the subsequent levels are:

FR_{81} – Support weight
FR_{82} – Keep the mould closed
DP_{81} – Dimensions of the Eye Bolt
DP_{82} – Dimensions of the Lock Strap

\[
\begin{align*}
\{ FR_{81} \} &= \begin{bmatrix} X \end{bmatrix} \{ DP_{81} \} \\
\{ FR_{82} \} &= \begin{bmatrix} 0 \end{bmatrix} \{ DP_{82} \} \\
\end{align*}
\]

(0.14)

Appendix I shows the overall hierarchical design decomposition and the complete design matrix for the moulds design that was derived.

Conclusions and future research

The main goal of this work was to apply the Axiomatic Design approach to moulds design. The methodology encompasses the identification and decomposition of the FRs and DPs into their respective hierarchies, by zigzagging between the functional domain and the physical domain. During this process, we found out that the design matrices identified were mostly coupled. Since our work is concerned so far with a characterization of current design practices, this raises some concerns about its efficiency, and points toward improvement opportunities.

The main difficulty identified in this study is related with the definition of FR and DP [4], since it was not trivial for the research team to clearly identify what is a FR and what is a DP. This will assume even more importance since customer needs aren’t yet linked with the FRs at this stage.
In future research the identification of customer’s needs must be undertaken. This will also allow us to address the identification and development of critical requirements, functions and architectures for a new product design [5]. The customer auscultation will be done by the conduction of semi-structured interviews. Then, it will be necessary to structure and rank the specific needs, and to establish the FR capable of fulfilling them (Customer mapping).

Several architectural concepts can be developed to fulfill the product functions. These solution alternatives will be created by mapping the FRs in the functional domain to a set of design parameters (DPs) in an adjacent physical domain, by the zigzag process. The number of plausible solutions for any given set of requirements depends on the designer. Thus, the design axioms proposed by Suh [1] will be used to determine the acceptable designs and select the best alternatives. The first axiom states that a good design should maintain the independence of functional requirements. After that, the superior solution must be selected. This choice must be made based on the second axiom, which establishes the information content as a relative measure for evaluating and comparing acceptable solutions, stating that a best design should have the smallest information content.

Afterwards, a quantitative analysis must be conducted with the objective of quantifying the relationships between the FR and DP, i.e., one must determine the elements $A_{ij}$ in the design matrix. Each $A_{ij}$ entry of $[A]$ relates the $i^{th}$ FR to the $j^{th}$ DP and must be evaluated at the specific design point in the physical space (unless $A_{ij}$ is a constant). This can be undertaken by the definition of partial derivates (equation(0.15)), and therefore, the design matrix can be easily populated if we do have a model available to support it:

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \quad (0.15)$$

The relationships between the FRs and DPs, can be linear or not, but in real world large-scale engineering systems they are mostly highly non-linear. Thus, it’s impossible to represent their relations in a straightforward, closed, analytical form. To populate a design matrix, some methods, such as a sequential DOE and surrogate modelling, can be carried out to build differentiable functions for the underlying relationships between the FRs and DPs (Simpson et al., 1997 cited by [6]). Once the differentiable functions are obtained, the design matrix elements between the FRs and DPs can be instantiated with actual values ($A_{ij}$) using equation(0.15). Afterwards, some analysis, for instance the reangularity and semangularity analysis (R/S), can be performed to assess the functional coupling degree of a current design based in Axiom 1. This quantitative analysis can be used to determine where design changes are needed to improve the current solution, or to identify the design with least coupling.

In summary, since no formal structural analysis is traditionally performed on the mould design, the AD approach, with the previous appointed limitations, seems a good methodology to understand and identify the main functions for the mould, and to define how to answer them through a structured and efficient methodology. Additionally, the AD method appears to be an excellent method to select a best solution, amongst several alternatives, and improve the weaknesses of an existing solution.

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Keywords

Metallic Moulds design; Axiomatic Design; Design axioms

References

# Appendix I

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